NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4065

TENSILE PROPERTIES OF INCONEL X SHEET UNDER RAPID-HEATING AND CONSTANT-TEMPERATURE CONDITIONS

By Ivo M. Kurg

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

Results of rapid-heating tests of Inconel X sheet are presented for nominal temperature rates of 0.2° F to 100° F per second under constant tensile load conditions. Yield and rupture stresses obtained under rapid-heating conditions are compared with the results of conventional tensile stress-strain tests at elevated temperatures. A marked increase in strength is observed with increased temperature rates. A temperature-rate parameter was used to construct master curves from which stresses and temperatures for yield and rupture can be predicted under rapid-heating conditions.

INTRODUCTION

Aerodynamic heating of aircraft and missiles has led to considerable research on the strength of materials at elevated temperatures. Recent investigations have shown that materials exhibit greater tensile strength when heated at rapid temperature rates than when tested under conventional constant-temperature test conditions. A number of reports on the effects of rapid heating of materials at high temperature rates have been published (for example, ref. 1). At the Langley Aeronautical Laboratory, tensile properties under rapid-heating conditions have been determined for several sheet materials - 7075-T6 and 2024-T3 aluminum alloys, Inconel, RS-120 titanium alloy, and HK31XA-H24 and AZ31A-O magnesium alloys (refs. 2 to 5).

The present paper gives the results of rapid-heating tests of Inconel X sheet heated to failure at nominal temperature rates of 0.2° F to 100° F per second under constant tensile load conditions. These results are compared with conventional tensile stress-strain data at constant elevated temperatures. A temperature-rate parameter for the prediction of yield and rupture temperatures is investigated.

MATERIAL AND SPECIMENS

The test specimens (fig. 1) were made from a single, annealed, 0.05-inch-thick sheet of Inconel X. The nominal chemical composition for the alloy (ref. 6) and the actual composition are given in table I. All specimens were cut with their longitudinal axes parallel to the rolling direction of the sheet. After being machined, the specimens were heat-treated for 1 hour at 1,400° F and then air cooled.

TEST PROCEDURE

Stress-Strain Tests

Conventional tensile stress-strain tests were performed at room and elevated temperatures to determine the change in Young's modulus with temperature and to compare yield and ultimate stresses with the results obtained from rapid-heating tests. The equipment and procedure were essentially the same as those described in reference 7. The specimens were exposed to the test temperature for 1/2 hour and then loaded to failure at a strain rate of 0.002 per minute. The stress-strain curve and a strain-time curve for each test were recorded simultaneously on an autographic recorder. The strain-time curve was used to control the strain rate during the test. The temperature during the exposure period was held within ±10° F of the desired test temperature. During the test, temperatures were held within ±5° F of the desired value. The yield stresses were determined with an accuracy of within ±2 percent and the ultimate stresses, within ±0.5 percent. In addition, three tests were performed with Tuckerman optical strain gages to establish Young's modulus at room temperature more accurately.

Rapid-Heating Tests

The equipment and procedure for rapid-heating tests were essentially the same as those described in references 2 and 3. The specimens were loaded at room temperature to the desired stress level by a dead-weight loading system and were then heated to failure at a constant temperature rate. Arbitrarily chosen stress levels of 20, 40, 60, and 80 ksi were used. Heating was achieved by passing an electric current directly through the specimen. Strains were measured over a 1-inch gage length by two differential transformer gages connected to the specimen through lever arms and gage frames. The thermocouples were spotwelded to the specimen with a commercial controlled-condenser-discharge spotwelder designed for that purpose. In rapid-heating tests the accuracy of strain measurements was within ±2 percent and the accuracy of the temperature measurements was within $\pm 5^{\circ}$ F. The thermal expansion characteristics were determined from rapid-heating tests at a stress of 0.4 ksi.

RESULTS AND DISCUSSION

Stress-Strain Tests

The results of stress-strain tests are given in table II and are illustrated in figures 2 to 4. Typical stress-strain curves for various test temperatures are shown in figure 2. The 0.2-percent-offset yield stresses are indicated by a tick mark on each curve. The variation of the yield and ultimate stresses with temperature is shown in figure 3, and the variation of Young's modulus with temperature is shown in figure 4. The dashed portion of the curve in figure 4 is extrapolated; it agrees closely with the values given in reference 8.

Rapid-Heating Tests

The results of the rapid-heating tests of the material are given in table III and are illustrated in figures 5 to 8. The thermal-expansion curve is illustrated in figure 5 and the average coefficients of thermal expansion determined from that curve are listed in table IV.

The strain-temperature histories at four stress levels for temperature rates from 0.2° F to 93° F per second are shown in figure 5. The families of curves for each stress level are spaced for ease of reading. These curves represent total strains which include thermal, elastic, and plastic strains. Until plastic deformation occurs, the experimental curves coincide with the curves representing the sum of the calculated thermal and elastic strain. The elastic strains were calculated by use of the Young's modulus curve given in figure 4. Yield temperatures, which are defined as temperatures at which a plastic strain of 0.2 percent occurs, are determined at an offset of 0.2 percent from the calculated strain curve, as indicated by the tick marks.

In figure 6, yield and rupture temperatures are plotted against the temperature rate on a logarithmic scale. The experimental curves for each stress level are represented by the solid lines. Both yield and rupture temperatures increase with the temperature rate. The relationship between yield temperatures and the logarithm of the temperature rate is linear at each stress level for the whole range of temperature rates used. For rupture, this relationship is linear up to about 20° F per second.

The rapid-heating and tensile stress-strain test results are compared in figures 7 and 8. The solid curves representing the rapid-heating test results for four temperature rates were cross-plotted from the experimental curves in figure 6. The stress-strain results represented by the dashed lines are from figure 3. For temperature rates of 0.2° F per second and less, the yield and rupture stresses from rapid-heating tests are lower than the yield and ultimate stresses from stress-strain tests. For temperature rates from about 2° F per second upward, the yield and rupture stresses from rapid-heating tests are higher than the yield and ultimate stresses from stress-strain tests. As the temperature rate increases, this difference becomes very large. The effect of temperature rate on the stress for yield and rupture at a given temperature is appreciable. For example, at 1,600° F, the rapid-heating yield stress at 100° F per second is 2.5 times higher than the corresponding stress for a temperature rate of 0.2° F per second. Similarly, at the same temperature, the rupture stress for 100° F per second is slightly more than twice the stress for 0.2° F per second.

Master curves for the prediction of temperatures or stresses at yield and rupture (figs. 9 and 10) were obtained by means of linear temperature-rate parameters according to the method described in reference 2. The parameter for the yield temperature is

$$\frac{T_y - 2600}{\log h - 15} \tag{1}$$

and for the rupture temperature

$$\frac{T_r - 100}{\log h + 20} \tag{2}$$

in which T_y is the yield temperature in °F; T_r the rupture temperature, in °F; and h the temperature rate, in °F per second. The agreement between predicted and actual yield and rupture temperatures is illustrated in figure 6, where the solid lines represent the experimental results and the dashed lines, the values predicted by using the master curves. The experimental and the predicted yield temperatures agree very closely; for rupture the agreement is also good except at about 100° F per second.

CONCLUSIONS

The following conclusions are based on the results of rapid-heating and conventional tensile stress-strain tests of Inconel X sheet.

1. Tensile rapid-heating tests indicate that at each stress level the yield and rupture temperatures increase considerably with the temperature rate. The yield temperatures vary linearly with the logarithm of the temperature rate for all rates tested. The variation of the rupture temperature with the logarithm of the temperature rate is linear up to about 20° F per second.

2. At a given temperature, the increase in yield and rupture stress with temperature rate is appreciable. Depending on the temperature rate used, the yield and rupture stresses obtained from rapid-heating tests can be higher or lower than the yield and ultimate stresses obtained from stress-strain tests.

3. Yield and rupture temperatures or the corresponding stresses can be predicted by means of master curves and temperature-rate parameters for the range of temperature rates investigated.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 6, 1957.

REFERENCES

1. Smith, W. K.: Relation of High-Heating-Rate Tests to Very-Short-Time Creep Tests. NAVORD Rep. 3403 (NOTS 995), U. S. Naval Ordnance Test Station (China Lake, Calif.), Mar. 15, 1955.

2. Heimerl, George J., and Inge, John E.: Tensile Properties of 7075-T6 and 2024-T3 Aluminum-Alloy Sheet Heated at Uniform Temperature Rates Under Constant Load. NACA TN 3462, 1955.

3. Heimerl, George J., Kurg, Ivo M., and Inge, John E.: Tensile Properties of Inconel and RS-120 Titanium-Alloy Sheet Under Rapid-Heating and Constant-Temperature Conditions. NACA TN 3731, 1956.

4. Gibbs, Thomas W.: Tensile Properties of HK31XA-H24 Magnesium-Alloy Sheet Under Rapid-Heating Conditions and Constant Elevated Temperatures. NACA TN 3742, 1956.

5. Kurg, Ivo M.: Tensile Properties of AZ31A-O Magnesium-Alloy Sheet Under Rapid-Heating and Constant-Temperature Conditions. NACA TN 3752, 1956.

6. Anon.: Engineering Properties of Inconel and Inconel "X". Tech. Bulletin T-7, The International Nickel Co., Inc., Rev. June 1953.

7. Hughes, Philip J., Inge, John E., and Prosser, Stanley B.: Tensile and Compressive Stress-Strain Properties of Some High-Strength Sheet Alloys at Elevated Temperatures. NACA TN 3315, 1954.

8. Anon.: Inconel "X" - A High Strength, High Temperature Alloy, Data and Information. The International Nickel Co., Inc., Dev. and Res. Div., Jan. 1949.

TABLE I

CHEMICAL COMPOSITION OF INCONEL X

[All values in percent]

Element	Nominal composition (a)	Actual composition (b)
Nickel	70 minimum	72.77
Chromium	14 to 16	14.98
Iron	5 to 9	6.82
Titanium	2.25 to 2.75	2.45
Columbium (and Tantalum)	.7 to 1.2	.96
Aluminum	.4 to 1.0	.76
Silicon	.5 maximum	.37
Manganese	.3 to 1.0	.74
Copper	.2 maximum	.06
Carbon	.08 maximum	.06
Sulfur	.01 maximum	.06

[a]From reference 6.

[b]Supplied by the manufacturer.

TABLE II

TENSILE STRESS-STRAIN PROPERTIES OF INCONEL X SHEET AFTER 1/2-HOUR TEMPERATURE EXPOSURE AND FOR A STRAIN RATE OF 0.002 PER MINUTE

Test temperature, °F	Yield stress, ksi	Ultimate stress, ksi	Young's modulus, psi	Elongation in 2 inches, percent
Room temperature	107.0	166.0	31.4×10^6	34
Room temperature	106.3	166.0	30.8	35
Room temperature*	107.0	166.0	30.8	32
Room temperature*	106.5	166.2	30.7	32
Room temperature*	105.3	164.5	30.7	29
400	99.4	156.8	30.8	33
600	94.4	145.2	28.7	30
800	96.2	143.6	27.8	36
800	91.6	140.8	29.9	**36
1,000	96.6	128.0	----------	16
1,000	98.8	131.0	24.9	13
1,000	97.4	133.0	25.3	16
1,000	95.7	128.3	25.4	14
1,200	92.9	103.0	23.6	4
1,200	94.5	104.0	23.4	5
1,200	98.4	106.1	25.0	4
1,300	92.9	94.5	22.6	3
1,400	76.5	76.5	----------	2
1,400	76.0	76.9	----------	2
1,400	78.9	78.9	21.9	2
1,500	60.0	60.0	21.2	4
1,600	39.4	39.7	----------	8
1,610	37.5	37.5	----------	9
1,740	8.1	8.1	----------	67
1,800	-----	10.3	----------	**64

*Tuckerman strain gages.

**Broke outside gage length.

TABLE III

TENSILE PROPERTIES OF INCONEL X SHEET UNDER RAPID-HEATING CONDITIONS

Stress, ksi	Temperature rate, °F/sec	Yield temperature, °F	Rupture temperature, °F	Elongation in 2 inches, percent
20.0	0.2	1,668	1,720	23
	.2	(a)	1,710	14
	.2	(a)	1,735	16
	2	1,700	(b)	(b)
	2	1,698	1,795	33
	20	1,765	1,885	31
	92	1,823	(c)	36
	93	1,842	2,000	28
	120	(a)	2,010	32
40.0	0.2	1,540	1,592	2
	.4	1,575	1,635	6
	2	1,607	1,650	6
	2	1,620	1,670	8
	20	1,687	1,760	22
	91	1,727	1,862	26
60.0	0.2	1,460	1,500	3
	2	1,519	1,580	4
	20	1,612	1,655	4
	92	1,659	1,747	10
80.0	0.2	1,334	1,402	2
	2	1,405	1,462	2
	20	1,492	1,525	2
	93	1,553	1,605	4

[a] Strain gages failed.

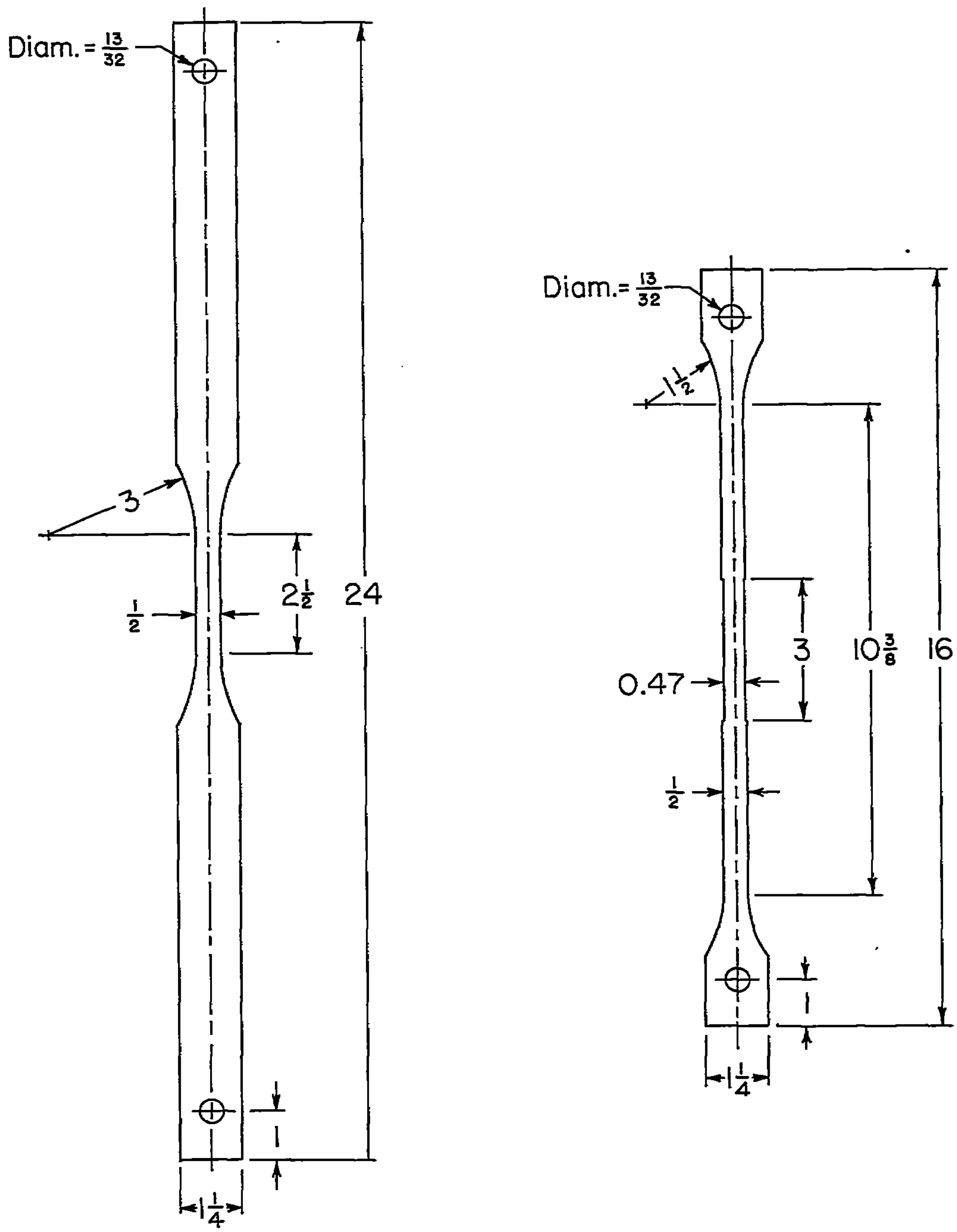
[b] No rupture.

[c] Thermocouple failed before rupture.

TABLE IV

THERMAL EXPANSION OF INCONEL X SHEET

Temperature range, °F	Thermal strain	Coefficient of thermal expansion per °F
80 to 200	0.00091	7.58×10^{-6}
80 to 400	.00249	7.78
80 to 600	.00409	7.86
80 to 800	.00576	8.00
80 to 1,000	.00749	8.14
80 to 1,200	.00934	8.34
80 to 1,400	.01144	8.67
80 to 1,600	.01385	9.11
80 to 1,800	.01692	9.84



(a) Stress-strain test specimen.

(b) Rapid-heating test specimen.

Figure 1.- Stress-strain and rapid-heating tensile test specimens. All dimensions are in inches.

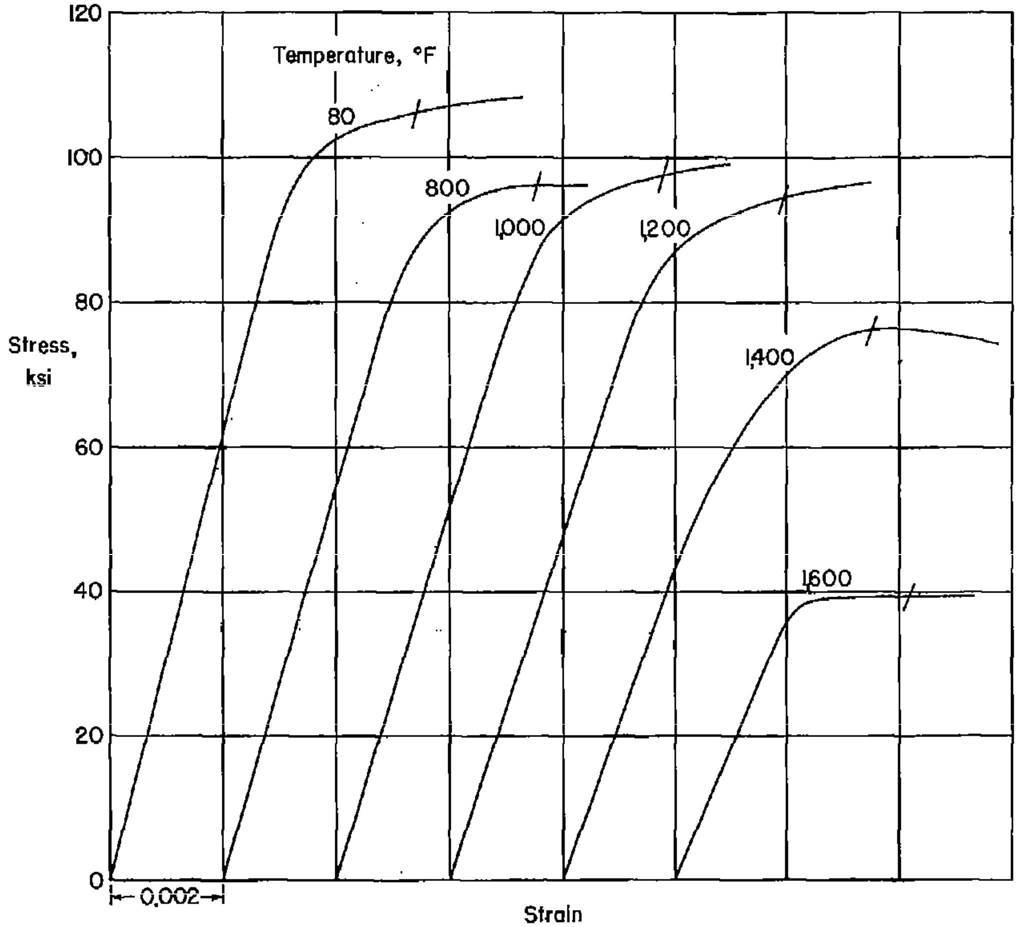


Figure 2.- Tensile stress-strain curves for Inconel X sheet after 1/2-hour exposure for a strain rate of 0.002 per minute. The tick marks indicate 0.2-percent-offset yield stresses.

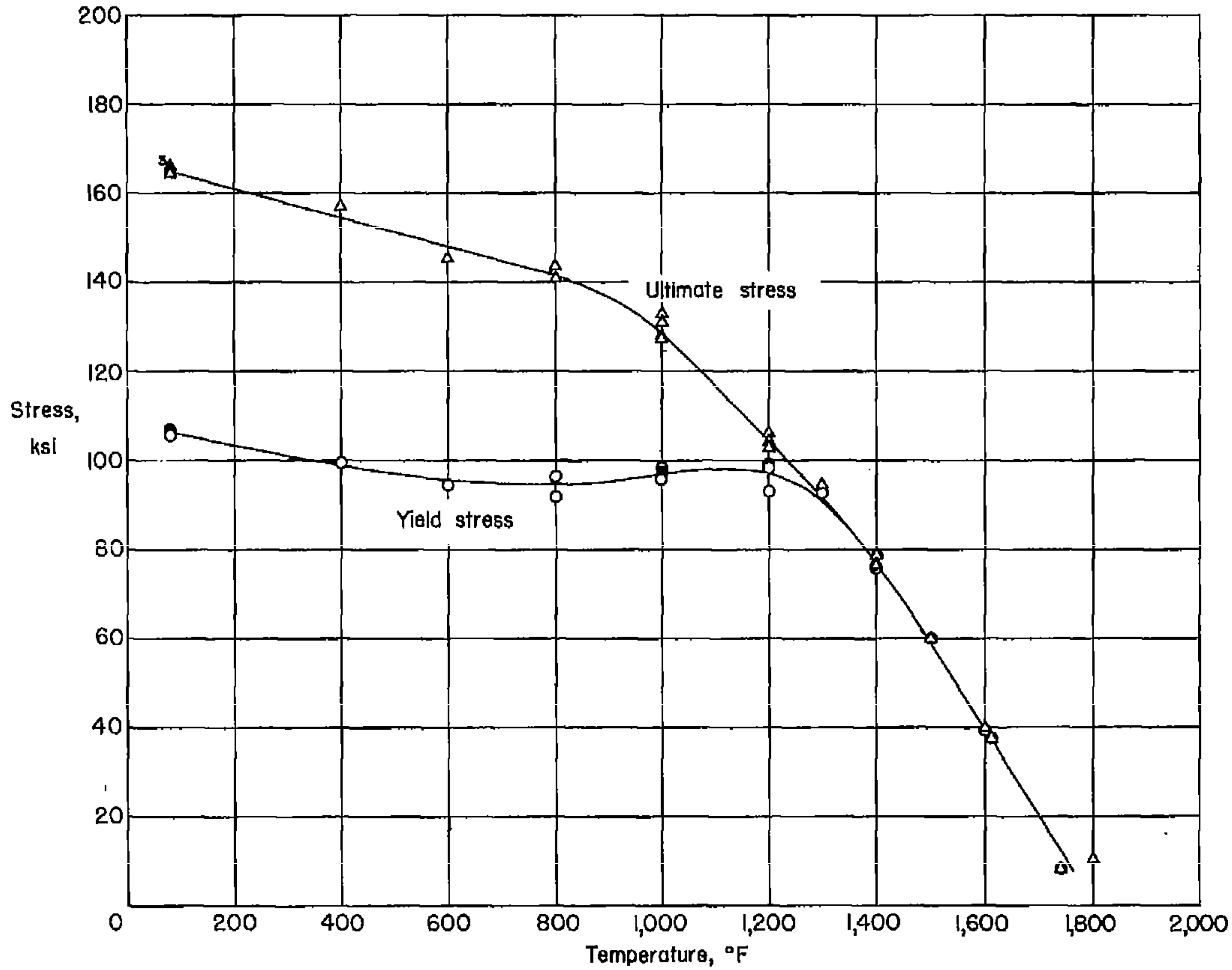


Figure 3.- Tensile yield and ultimate stresses for Inconel X sheet at elevated temperatures after 1/2-hour exposure for a strain rate of 0.002 per minute. Yield stress is for 0.2 percent offset.

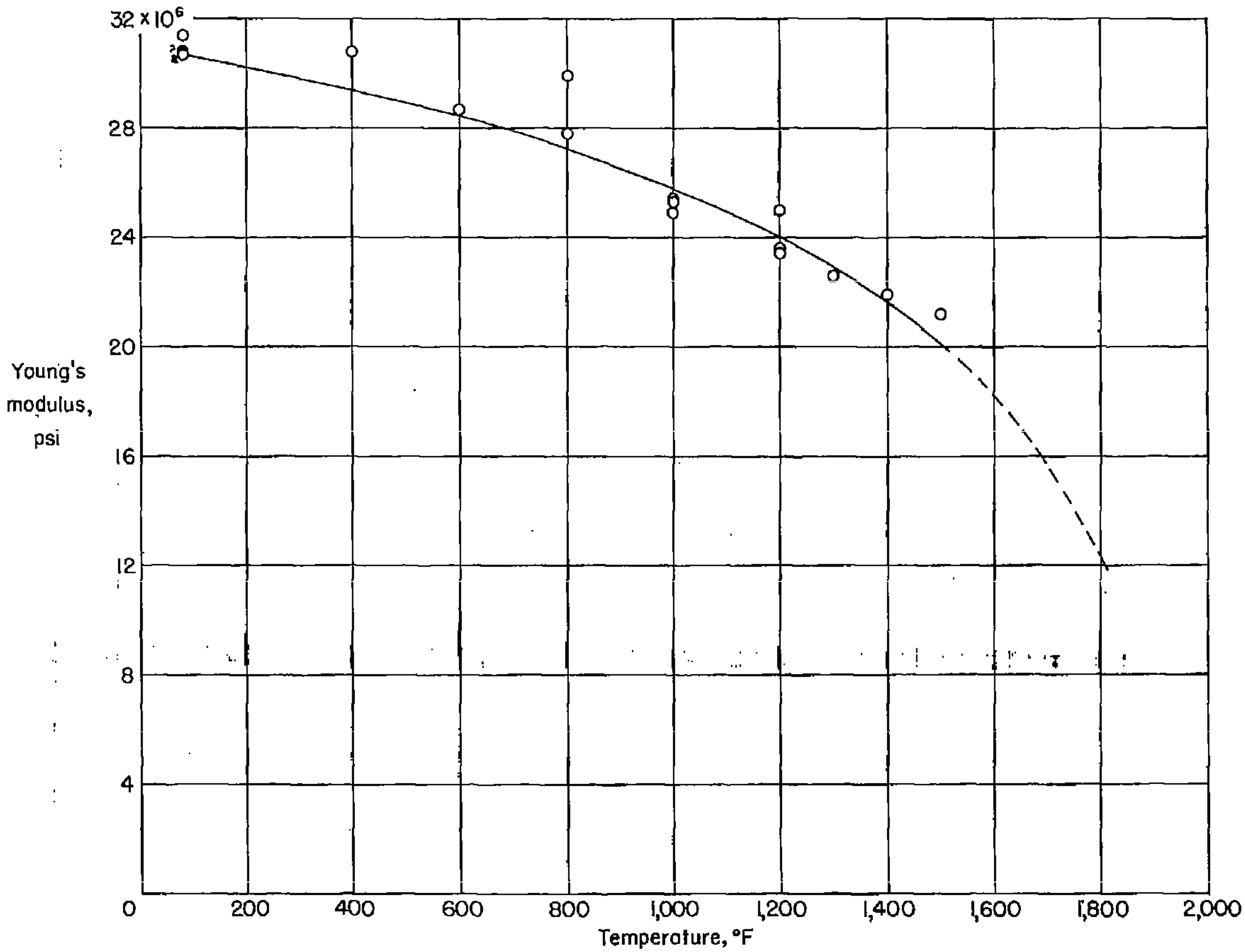


Figure 4.- Young's modulus of Inconel X sheet at elevated temperatures after 1/2-hour exposure.

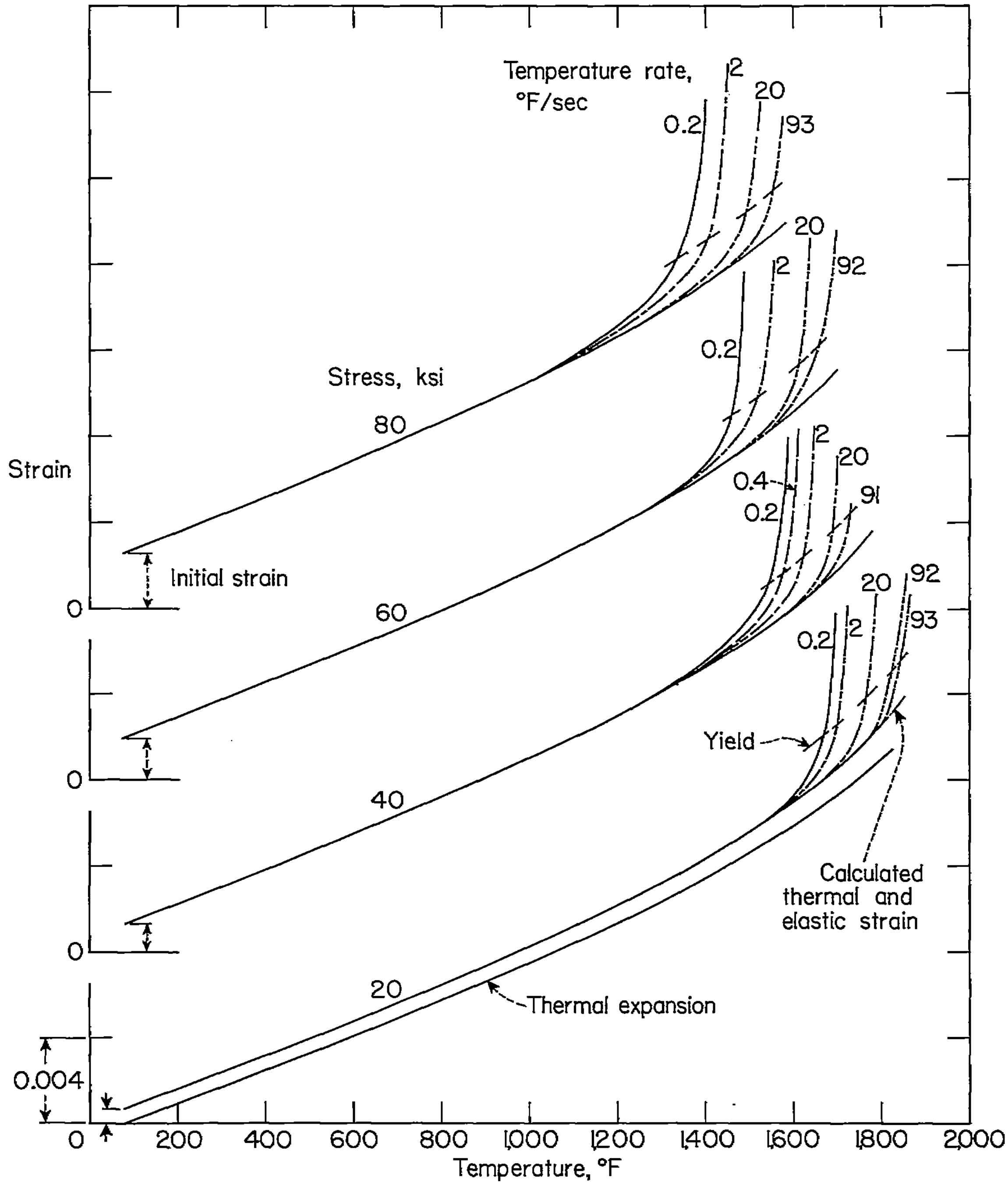


Figure 5.- Strain-temperature curves for Inconel X sheet for temperature rates of 0.2° F to 93° F per second for various stresses.

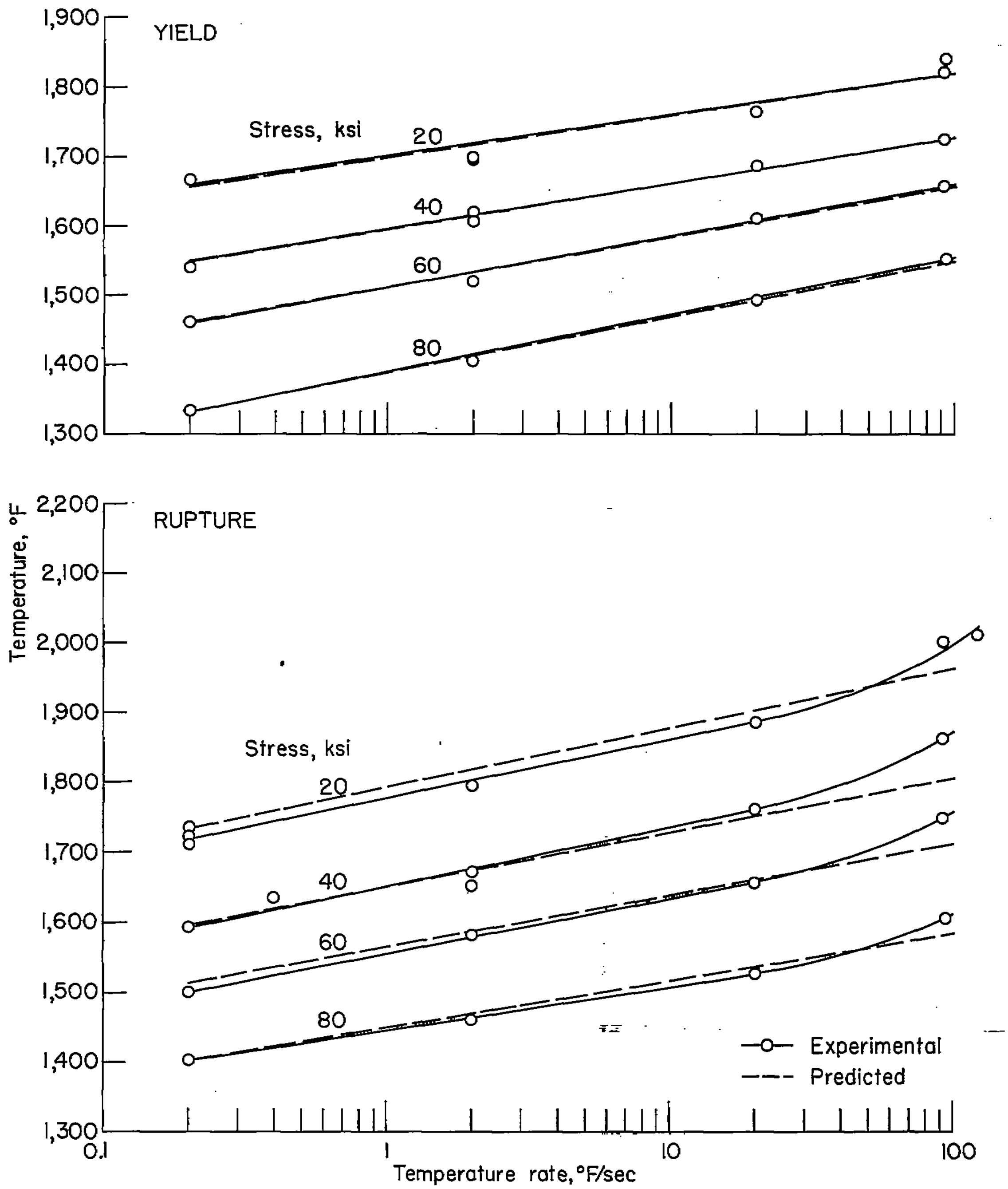


Figure 6.- Experimental and predicted yield and rupture temperatures for Inconel X sheet for temperature rates from 0.2° F to 120° F per second for various stresses.

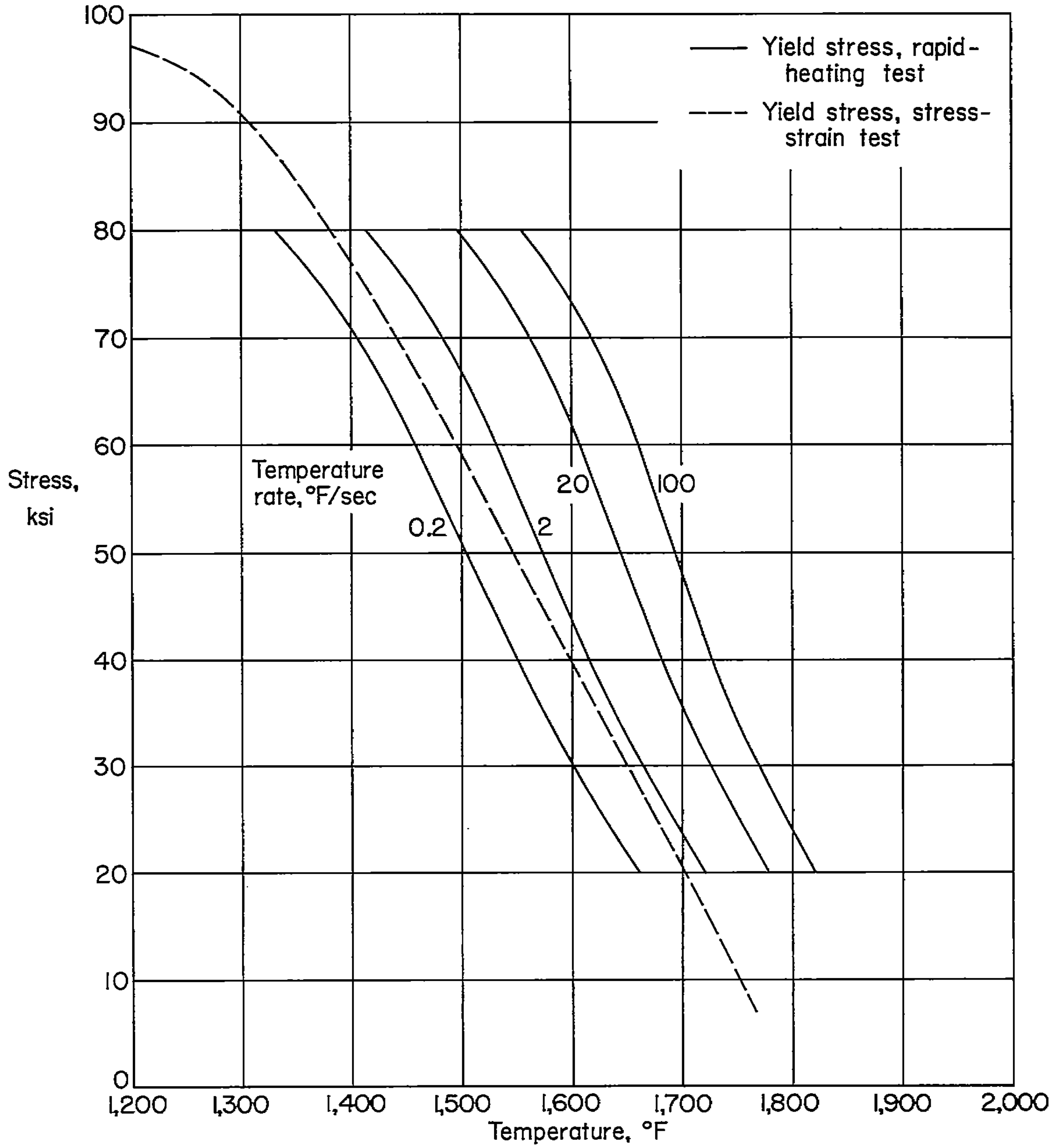


Figure 7.- Tensile yield stress of Inconel X sheet for rapid-heating tests from 0.2° F to 100° F per second and for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute.

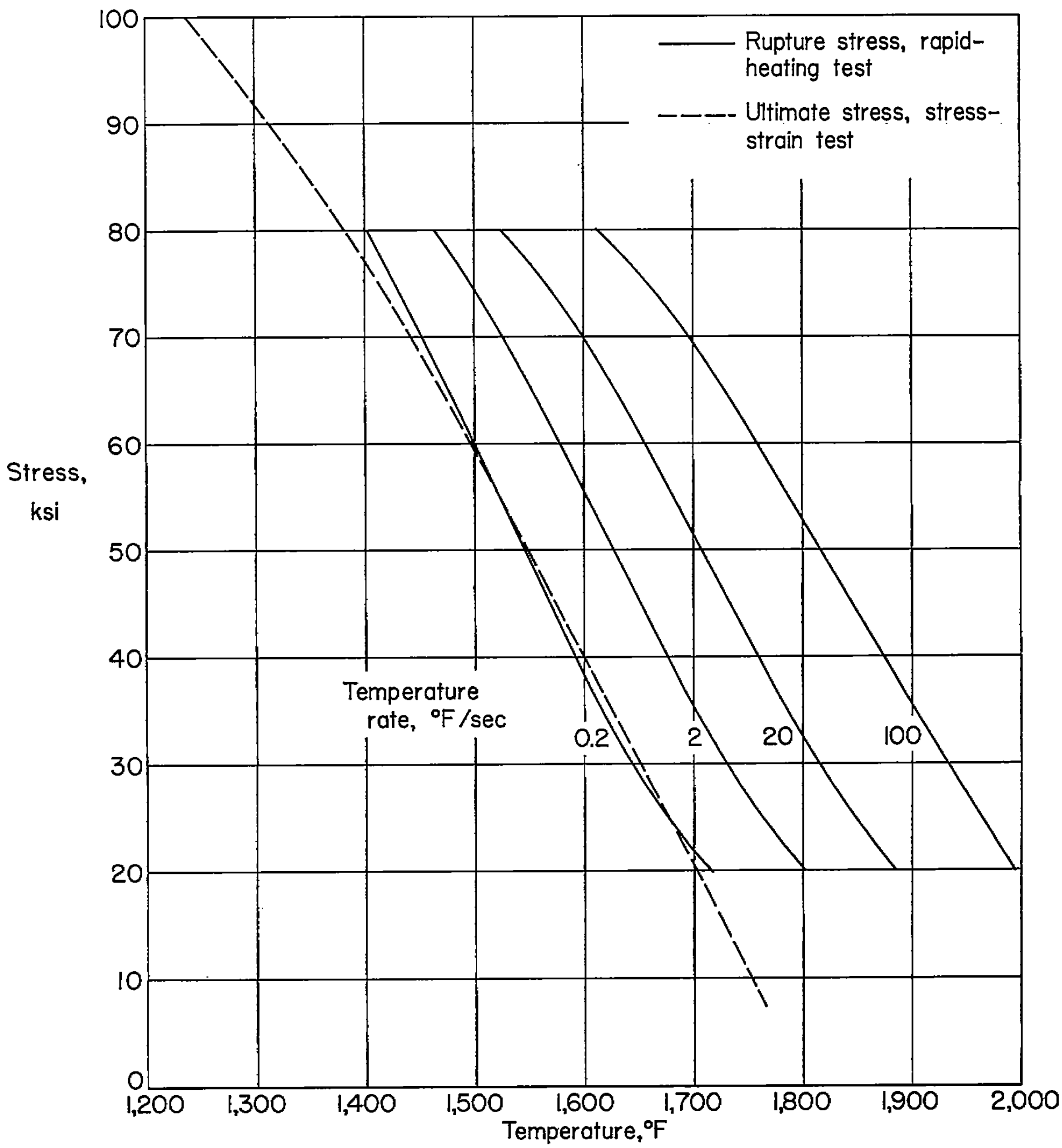


Figure 8.- Tensile rupture stress of Inconel X sheet for rapid-heating tests from 0.2° F to 100° F per second and tensile ultimate stress for stress-strain tests after 1/2-hour exposure for a strain rate of 0.002 per minute.

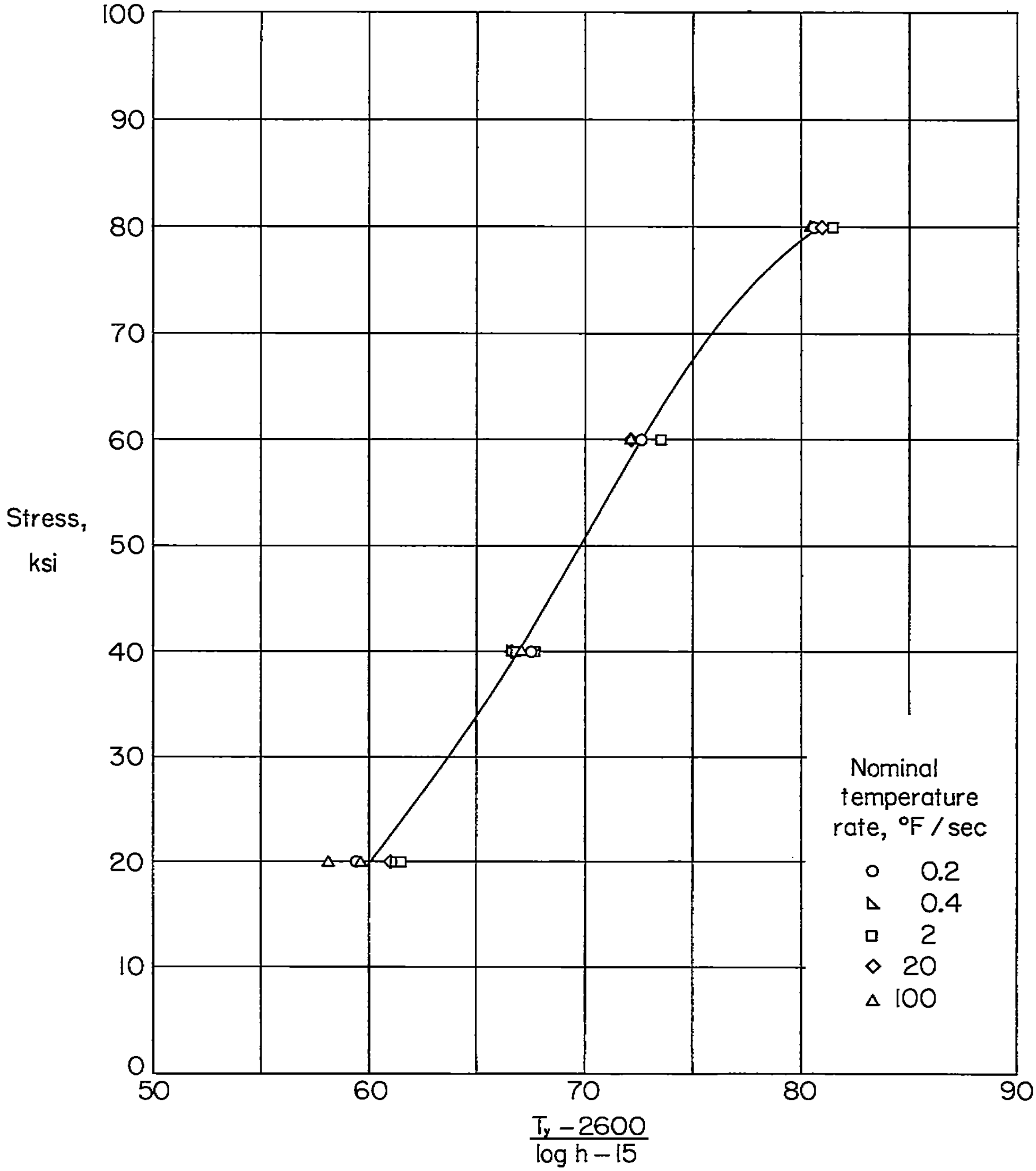


Figure 9.- Master yield-stress curve for Inconel X sheet using the temperature-rate parameter $\frac{T_y - 2600}{\log h - 15}$. (The yield temperature T_y is in °F and the temperature rate h is in °F per second.)

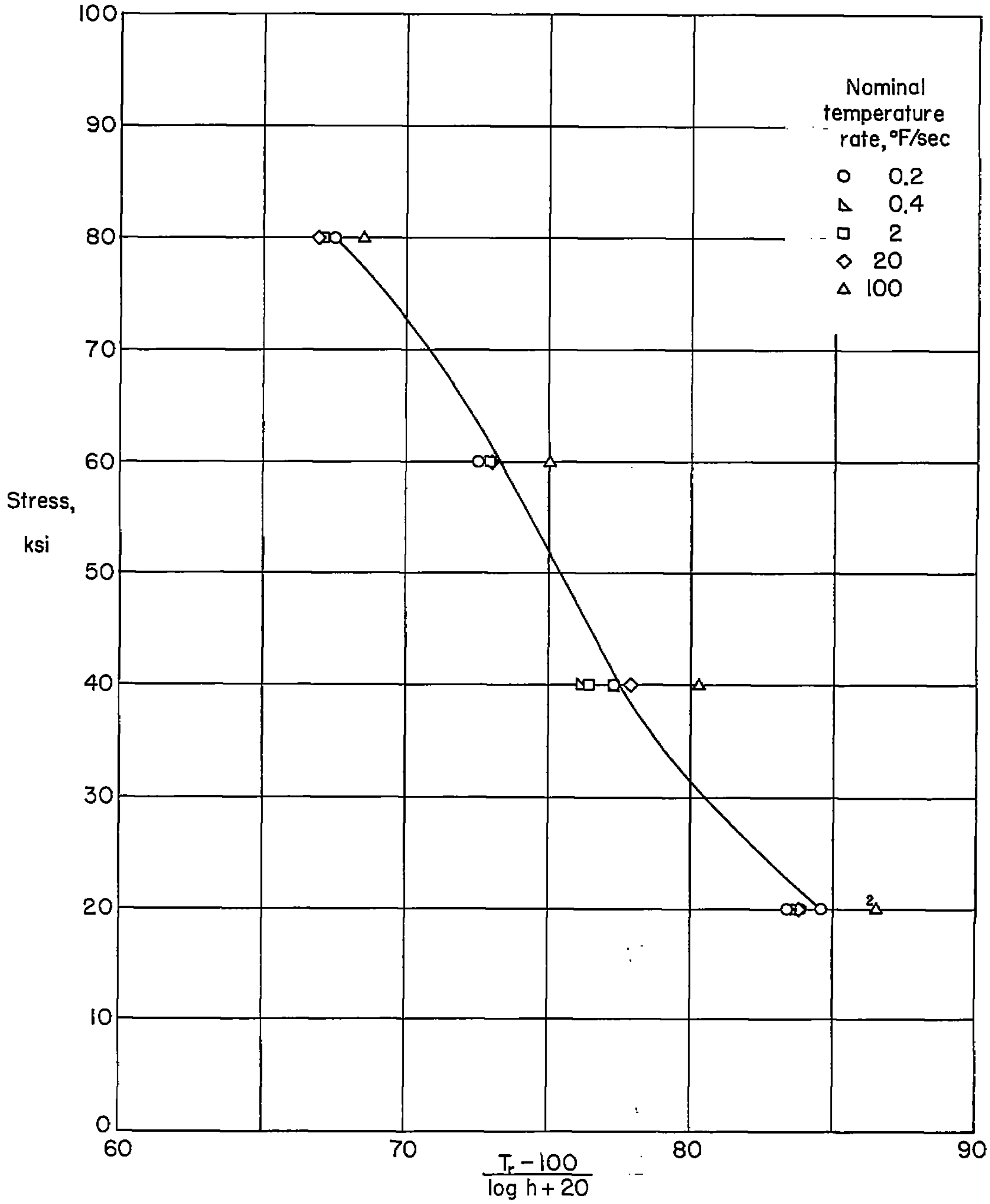


Figure 10.- Master rupture-stress curve for Inconel X sheet using the temperature-rate parameter $\frac{T_r - 100}{\log h + 20}$. (The rupture temperature T_r is in $^{\circ}F$ and the temperature rate h is in $^{\circ}F$ per second.)